

A Study on Highway Traffic Flow Optimization using Partial Velocity Synchronization

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Abstract—In this paper we present a study of highway traffic flow optimization using Partial Velocity Synchronization (PVS). PVS is a *Cellular Automaton* (CA) model that is extended by a communication layer providing the ability to exchange relevant information between vehicles. We show that it is possible to enhance traffic flow on highways significantly with a small number of velocity recommendations computed from the traffic conditions ahead. Furthermore we show that only a limited number of hops in an information chain is necessary to reschedule the vehicles on a given highway segment to avoid the formation of shockwaves. Our results show that traffic flow will be increased while travel time and emissions will be reduced dramatically.

Index Terms—Traffic Modeling, Congested Flow, Cellular Automaton, Vehicular Ad Hoc Networks

I. INTRODUCTION

Over recent decades, traffic demand on highways has increased significantly and is still doing so. In many regions the existing infrastructure has reached a capacity limit and cannot be extended easily [1]. This results in more and more drivers being stuck in congestion, causing billions of dollars worth of economic and ecological damage [2]. Besides the time loss, frequent switching between acceleration and deceleration makes driving very tedious and wastes energy as well increasing emissions.

In this paper we present a study on a new *Advanced Driver Assistance System* (ADAS) that is extended by a *Vehicular Ad Hoc Network* (VANET) to propagate additional information upstream in the traffic flow with the ability to react much earlier than is possible by relying solely on information from within the line of sight. The protocol presented here can be used to set individual speed limits. Compared to a spatially-fixed system such as information panels a more dynamic velocity adaptation is possible.

The simulations are performed on the basis of a *Cellular Automaton* (CA) model that is extended by a communication layer. The new protocol, *Partial Velocity Synchronization* (PVS), aims to give non-intuitive velocity recommendations to drivers to prevent shockwaves from forming and to reduce the formation of *phantom jams*. We show that only a small number of velocity recommendations is necessary to redistribute the upstream traffic in a way that can disperse congestions before the traffic inflow arrives.

The remainder of this paper is organized as follows. In Section II we describe the base model and our extension. In

section III, we discuss the results obtained from the simulations. Finally, a conclusion is drawn in Section IV.

II. PARTIAL VELOCITY SYNCHRONIZATION

This section provides an overview of the *Partial Velocity Synchronization* (PVS) protocol. For a complete description please refer to the original paper [3]. PVS is an extension of the well-established *Velocity Dependent Randomization* (VDR) model [4]. It specifies a communication channel between vehicles to enable the transfer of recent traffic metrics.

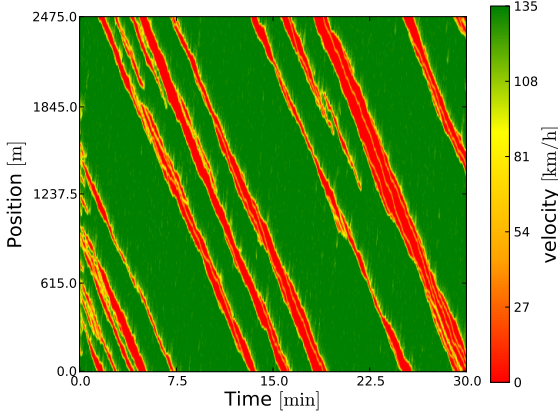
The VDR model is a *Cellular Automaton* (CA) model based on simple rules, executed in fixed time steps. This models are particularly applicable for highway traffic. The most popular model in this class is the *Nagel-Schreckenberg* (NaSch) model, introduced by Kai Nagel and Michael Schreckenberg [5]. The VDR model is based on the NaSch model but extends it with a probabilistic factor to represent the human tendency to dally. More precisely, this tendency is represented by a probabilistic factor that depends on the actual velocity. In fact only two cases are distinguished, namely a moving driver having a much lower probability of dallying (p_m) compared to a stationary one (p_s). This probabilistic extension is necessary to model the so-called *phantom jams* that are caused mainly by human inefficiency [6]. The model equation for driver inattention depends on the actual velocity:

$$P_d(v_\alpha(t)) := \begin{cases} p_s & \text{if } v_\alpha(t) = 0 \\ p_m & \text{else} \end{cases} \quad \text{where } p_m \ll p_s \quad (1)$$

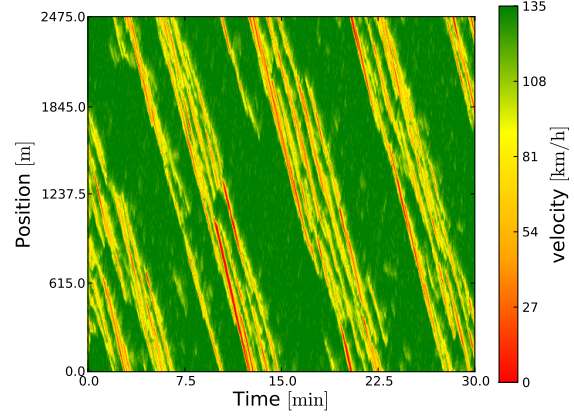
The main principle of these traffic models is to ensure collision-free driving. In the VDR model this is ensured by the fact that drivers will adapt their velocity to the preceding vehicle if its distance is less than would be covered at the demanded velocity in the next time-step. This implies, however, that the maximum distance for reactions and hence the line of sight is given by the maximum allowed velocity.

The communication channel introduced with PVS extends the awareness horizon of the motorists far beyond the line of sight. The objective of the protocol is to use the additional information to redistribute the traffic upstream in such a way that the already decelerating or stationary vehicles will have enough time to leave the critical region downstream before the new inflow arrives.

In practice, the communication protocol adds two new rules to the VDR model, namely *notification* and *anticipation*:



(a) Space-Time diagram for VDR



(b) Space-Time diagram for PVS

Fig. 1: comparison of space-time diagrams for 330 cells and $\rho = 33$ vehicles/km

a) *Notification*: A vehicle that has to decelerate, or is not allowed to accelerate, under the rules of the VDR model, sends a message m upstream to the following vehicle containing its actual position $x_\alpha(t)$, the actual time t and velocity $\hat{v}_\alpha(t)$. A modification to this rule is that vehicles with velocities less or equal to 1 km/h always send this message, which is given by the vector:

$$m_\alpha(t) = [x_\alpha(t), t, \hat{v}_\alpha(t+1)]$$

b) *Anticipation*: Vehicles receiving the *notification* message from the preceding vehicle calculate an anticipated velocity as follows:

$$v_{\alpha,\text{ant}}(t+1)^{(1)} = \max([\lceil (d_\alpha(t) + \hat{v}_{\alpha+1}(t)) / 2 \rceil, 1] \quad (2)$$

where $v_{\alpha,\text{ant}}(t+1)$ is the anticipated velocity considering the estimated distance $d_\alpha(t) + \hat{v}_{\alpha+1}(t) \cdot \Delta t$ to the preceding vehicle $\alpha+1$ after its current move. The multiplication by the time-step Δt can be ignored because it is generally set to 1s. If the anticipated velocity is smaller than the desired velocity (by VDR rules) the system notifies the driver to adapt his velocity to $v_{\alpha,\text{ant}}(t+1)$.

Algorithm 1 PVS model algorithm

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1: procedure PVS()
2:    $p = P_d(v_\alpha(t))$ 
3:    $d(t) = x_{\alpha+1}(t) - x_\alpha(t) - 1$ 
4:    $v_\alpha(t+1) = \min(v_\alpha(t) + 1, v_{\max}, d(t))$ 
5:   if RECEIVE() then
6:      $v_{\alpha,\text{ant}}(t+1) = \max(\lceil d(t) + v_{\alpha+1}(t)/2 \rceil, 1)$ 
7:      $v_\alpha(t+1) = \min(v_{\alpha,\text{ant}}(t+1), v_\alpha(t+1))$ 
8:      $p = P_d(\kappa(t), v_\alpha(t))$ 
9:   end if
10:  if RANDOM(0,1)  $\leq p$  then
11:     $v_\alpha(t+1) = v_{\alpha,\text{ant}}(t+1) - 1$ 
12:  end if
13:  if  $v_\alpha(t+1) < v_\alpha(t) \vee v_\alpha(t+1) \leq 1$  then
14:    SEND( $v_\alpha(t+1)$ )
15:  end if
16: end procedure

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The idea is to adapt the actual velocity to cover half of the estimated distance after the current step. This must be done

to ensure a minimal distance that allows one additional move considering the worst case, namely that the preceding car stops immediately in the next time step.

Further, we extend the velocity-dependent randomization function to take into account two input parameters, namely the velocity $v_\alpha(t)$ and an action event parameter $\kappa(t) \in \{0, 1\}$. Two states are possible for $\kappa(t)$: 0 if no message is received, and 1 otherwise.

$$P_d(\kappa(t), v_\alpha(t)) = \begin{cases} p_n & \text{if } \kappa(t) = 1 \\ P_d(v_\alpha(t)) & \text{else} \end{cases} \quad (3)$$

where p_n is the probability of dallying for a notified motorist. It holds true that $p_n < p_m \ll p_s$.

The PVS protocol is designed to improve the actual situation on highways. This means that we have to deal with humans and their imprecision. Although PVS is intended to be an *Advanced Driver Assistance System* it is also applicable to fully-autonomous vehicles, which are accommodated by setting the probabilistic factors to zero, resulting in completely deterministic behavior.

The model behavior for one vehicle performing a distinct simulation round is given as pseudo code in Algorithm 1. For more information we refer to our original paper [3].

III. EVALUATION

In the simulations performed, only single-lane traffic has been considered. Furthermore, the simulated traffic environment is a closed loop, meaning there are neither inflows nor outflows to disturb the simulated traffic. These constraints, as a first step, allow us to investigate an upper bound for traffic flow optimization.

The simulation parameters are as follows: The cell size is $|x_\alpha| = 7.5$ m, which represents the standard length of a vehicle plus a safety gap. For all simulation runs, the length of the observed road segment is given as $L = 1330$ cells = 9.75 km. The maximum allowed velocity

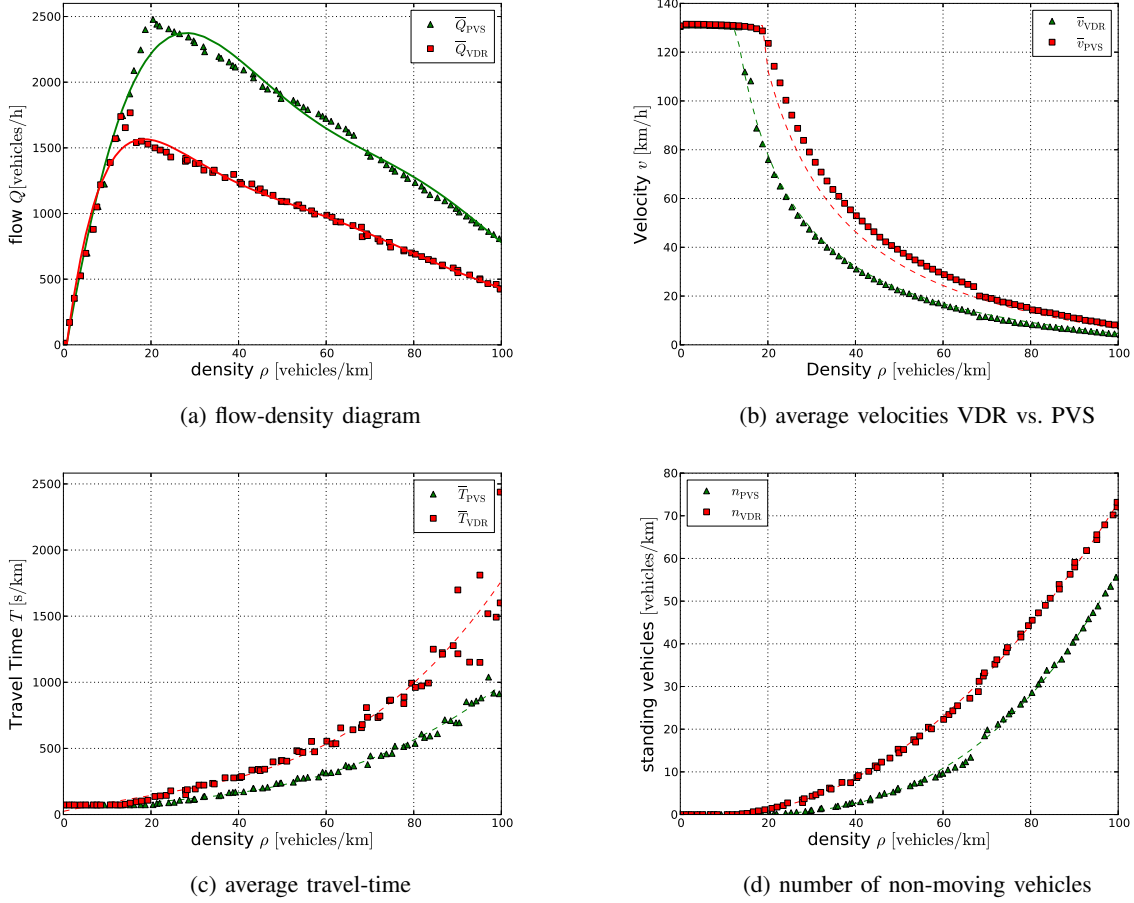


Fig. 2: Comparison of macroscopic results for VDR versus PVS

is set to $v_{\max} = 5 \text{ cells/s} \approx 135 \text{ km/h}$. Simulations were performed for densities starting at $\rho = 1 \text{ veh/km}$ up to $\rho = 134 \text{ veh/km}$ and statistical values are taken from 10800 simulation rounds for each density, resulting in an overall simulation time $T_{\text{overall}} = 300 \text{ h}$. The probabilistic values for human behavior are set to $p_n = 0.05$, $p_m = 0.15$ and $p_s = 0.5$. This means that a motorist alerted by PVS has a probability of 5% of not obeying the recommendation. The other probabilistic factors state that a moving driver tends, with a probability of 15%, to dally whereas a stationary one has a probability of 50% not to accelerate even if he could.

Figure 1 represents the velocity distribution on a time-space diagram for a constant overall density $\rho = 33 \text{ vehicles/km}$. The red zones in Figure 1a depict the propagation of the slowdowns upstream, whereas with Figure 1b it becomes obvious that the strategy of PVS almost completely absorbs the shockwaves and so limits the number of slow-downs. There are still congested regions, but nearly no standing vehicles. One major result is that the traffic is better distributed over the available road section, so avoiding unnecessary decelerations and accelerations.

Figure 2 depicts comparisons of flow density, average velocity, average travel time and average number of non-moving

vehicles for simulations with the VDR model versus the PVS model for single-lane traffic. The graphs can be divided into two distinct regions, where the first, reaching from zero density to the inflection point of the flow-density diagram is called the *free-flow phase* and the region thereafter is called the *congested phase*. The metastable branch of the VDR model in Figure 2a is caused by two completely different behaviors in the same density regions [4], [7]. This is caused by the fact that inflow to, and outflow from, congested areas are controlled by different probabilities. The results of the average velocity (Figure 2b) and travel time (Figure 2c), clearly show that we are able to increase the average speed and hence reduce the average time needed to pass the given road segment by up to 30%. In Figure 2d we see that with PVS we also have up to 60% fewer standing vehicles and for densities below 40 vehicles/km there are nearly none.

In Figure 3 some properties of the proposed PVS message protocol are shown. Like the graphs for the macroscopic traffic metrics, given in Figure 2, the results for the messages can be divided into two branches. These segments are the *free-flow phase* before the inflexion point, and the *congested phase* thereafter. The information hop-count, given in Figure 3c, is the average length of a continuous velocity

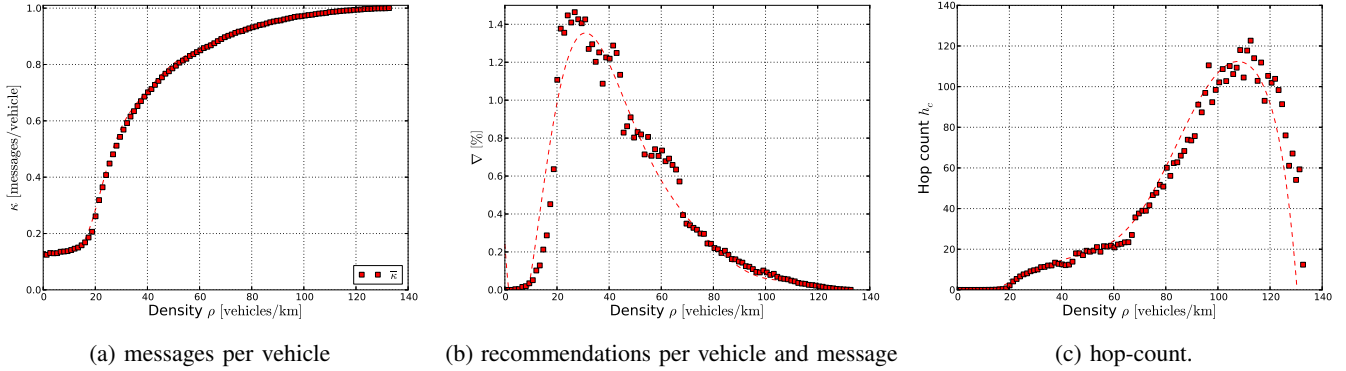


Fig. 3: Communication Protocol evaluation

recommendation chain upstream against density. This means the value is increased if a vehicle receives a message from the preceding vehicle and computes the necessity for a velocity recommendation to the driver and of whether to send the information further upstream. Figure 3a depicts the average number of messages per vehicle over density. In the free-flow phase, there are nearly no messages emitted and hence, the driver receives no recommendations and the information hop-count is zero. The average number of broadcast messages per vehicle increases asymptotically towards 1 very rapidly. Due to the increasing density, more vehicles have to perform a braking maneuver, releasing a message. In the region of maximal density only a very low number of vehicles are able to move because only a low number of cells are not occupied. In this situation nearly every road user broadcasts a message. The number of recommendations per vehicle and message (Figure 3b) jumps from zero to 1.4% at the inflexion point and remains stable until approximately one third of the maximum density. This region is to be considered the sensitive range of the PVS protocol. The decrease in recommendations after this point is caused by the shortening of distances between vehicles with increasing density. This means that most decelerations happen within drivers' awareness horizon. They are controlled by the deceleration rule of the VDR model itself and are not triggered by a PVS recommendation.

IV. CONCLUSION

In this paper we show that it is possible to set up an *Advanced Driver Assistance System* (ADAS) with limited network capabilities, provided by a VANET, to increase traffic flow as well as the average travel velocity and so reduce average travel-time and emissions.

A system based on *Partial Velocity Synchronization* (PVS) will be able to provide individual velocity recommendations to motorists (or operate in a fully automated vehicle) to avoid hard braking maneuvers. This will certainly improve driving convenience and road safety. Another advantage of such a system will be the reduction of fuel consumption and all its drawbacks.

Though the use of *Partial Velocity Synchronization* (PVS),

only a low number of velocity recommendations are adequate to improve highway traffic flow significantly. Distributing only relevant traffic information upstream in the traffic flow over a limited number of hops is sufficient to redistribute the approaching traffic such that forming shockwaves can be absorbed.

Future work will focus on the proportion of the participants needed to achieve a significant improvement in highway traffic flow.

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